

Flavor unification, dark matter, proton decay and other observable predictions with low-scale S_4 symmetry

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Abstract

We show how gauge coupling unification is successfully implemented through non-supersymmetric grand unified theory, $SO(10) \times G_f$ ($G_f = S_4, SO(3)_f, SU(3)_f$), using low-scale flavor symmetric model of the type $SU(2)_L \times U(1)_Y \times SU(3)_C \times S_4$ recently proposed by Hagedorn, Lindner, and Mohapatra, while assigning matter-parity discrete symmetry for the dark matter stability. For gauge coupling unification in the single-step breaking case, we show that a color-octet fermion and a hyperchargeless weak-triplet fermionic dark matter are the missing particles needed to complete its MSSM-equivalent degrees of freedom. When these are included the model automatically predicts the non-supersymmetric grand unification with a scale identical to the minimal supersymmetric standard model/grand unified theory scale. We also find a two-step breaking model with Pati-Salam intermediate symmetry where the dark matter and a low-mass color-octet scalar or the fermion are signaled by grand unification. The proton-lifetime predictions are found to be accessible to ongoing or planned searches in a number of models. We discuss grand unified origin of the light fermionic triplet dark matter, the color-octet fermion, and their phenomenology.

1 Introduction

The standard model (SM) gauge theory based upon $SU(2)_L \times U(1)_Y \times SU(3)_C$ ($\equiv G_{213}$) has enjoyed tremendous success by virtue of its excellent agreement with numerous experimental data. Nevertheless the SM has several shortcomings some of which are circumvented when the model emerges from a grand unified theory (GUT) [1, 2, 3]. Apart from providing solutions on certain fundamental issues [4], GUTs predict gauge boson mediated proton decay via $d = 6$ operators and, in particular, the decay mode $p \rightarrow e^+ \pi^0$ has been the hall mark of grand unification. Predictions of gauge boson mediated proton decays in nonsupersymmetric (non-SUSY) GUTs are neat and robust compared to the corresponding predictions in supersymmetric GUTs which are affected by complications due to Higgsino mediated proton decays via $d = 5$ operators [5, 6]. Predictions on the proton decay in GUTs with or without supersymmetry (SUSY) have called for dedicated experimental searches to testify the predicted phenomena [7, 8]. But GUTs may not provide a satisfactory answer to fermion masses and mixings which may need additional flavor symmetries. In fact, experimental evidences of masses and large mixings of neutrinos has triggered interests in flavor symmetries leading to the suggestions of grand unification symmetry of flavor including $SO(10) \times G_f$ ($G_f = S_4, SO(3)_f, SU(3)_f$) [9, 10, 11, 12, 13, 14, 15, 16].

Recently Hagedorn, Lindner, and Mohapatra (HLM) [10] have examined an interesting model based upon the non-SUSY SM gauge structure as a possible solution to the fermion flavor problem with $G_{213} \times S_4$ symmetry at low scales. It predicts a rich structure of neutral and charged Higgs scalars near the TeV or lower scales which can be tested at Tevatron, LHC or planned accelerators. However, suppressed flavor-changing neutral current (FCNC) effects near electroweak scale may suggest that the scale of spontaneous S_4 symmetry breaking could be higher, \sim (few-10) TeV instead of being near the electroweak scale. In such a case HLM type of analysis can be carried out with renormalization group (RG)-extrapolated values of fermion masses and mixings [17] at 1 – 10 TeV scale as has been done in [11, 12, 13] and in a number of other models. Such HLM type of model with spontaneous S_4 braking at $\sim 1 - 10$ TeV would lead to the SM with only one Higgs doublet below the TeV scale.

In SUSY $SO(10) \times S_4$ with R-parity conserving intermediate symmetry $SU(2)_L \times SU(2)_R \times U(1)_{B-L} \times SU(3)_c \times S_4$ ($g_{2L} = g_{2R}$) at the type-I see-saw scale [12], apparently there is no signature of the underlying flavor symmetry to be tested by accelerator searches. While the gauge hierarchy problem certainly prefers a supersymmetric $SO(10) \times G_f$ model, in the absence of any evidence of supersymmetry at low energies and for the sake of simplicity alone, prospects of minimal non-SUSY $SO(10) \times G_f$ should be thoroughly explored and confronted with experiments.

More recently, interesting attempts have been made through non-SUSY $SO(10)$ to exploit matter-parity origin of dark matter (DM) [18]. As signals of of grand unification in the single-step breaking of non-SUSY $SO(10)$, an inert scalar doublet along with a scalar singlet [18] have been suggested as DM candidates. In another independent study, a non-standard weak triplet fermion $F_\sigma(3, 0, 1)$ with zero hyper-charge and TeV scale mass, suggested earlier from phenomenological grounds [19], has been identified as DM candidate [20].

In this work while attempting grand-unification completion of the HLM type model we identify two interesting models :(i) A single-step breaking model where $\sim\text{TeV}$ scale masses of a fermionic triplet dark matter as well as a color-octet fermion are predicted by grand unification; (ii) A two-step breaking model with Pati-Salam intermediate symmetry where TeV scale masses of the fermionic triplet DM and a color-octet scalar or fermion are accommodated by grand unification. We show how light masses of both types of fermions are obtained from the adjoint fermion representation $(45_F, 1) \subset SO(10) \times G_f$ and discuss their phenomenology. The proton lifetime predictions made in a number of the cases are accessible to ongoing and planned searches. Although the production cross section for direct detection of DM is known to be small at present LHC energies and luminosity, there is agreement of recently predicted fluxes with PAMELA positron excess with corresponding absence of anti-proton excess for energy ≤ 200 GeV. Large pair production cross section and absence of superpartners at accelerator energies would indicate towards the presence of color-octet fermions of this model. Whereas $SO(10)$ grand unification without flavor symmetry signals the presence of the fermionic triplet DM with TeV scale mass, the color-octet fermion needed for completion of the same grand unification has very large mass (7×10^{10} GeV) [20] which is impossible to manifest at accelerator energies. In the present model, however, both the fermion masses being in the $\sim \text{TeV}$ scale, are subject to experimental tests at the accelerators.

The non-SUSY $G_{213} \times S_4$ model with six doublets at lower scale has an interesting prediction. Matching the degrees of freedom relevant for gauge coupling unification with the minimal supersymmetric standard model (MSSM), we show that the color-octet fermion and the hyperchargeless weak-triplet fermionic DM are the missing non-trivial elements from the low-scale flavor symmetric gauge theory. As such their inclusion at $\sim\text{TeV}$ scale naturally predicts non-SUSY grand unification with a scale identical to the MSSM-GUT scale.

This paper is organized in the following manner. In Sec. 2 we discuss briefly the HLM type model with $G_{213} \times S_4$ symmetry. In Sec.3 after showing absence of unification in the HLM type model, the minimally modified single-step breaking scenario is presented with grand unification signals. In this section we also discuss predictions on the proton lifetime. In Sec.4 we discuss phenomenology of light fermions. The two-step breaking models including Pati-Salam intermediate gauge symmetry are discussed in Sec. 5. Summary and conclusions are stated in Sec. 6.

2 The standard gauge theory with low-scale S_4 symmetry

In this section we discuss salient features of the $G_{213} \times S_4$ model of the type used in ref. [10] and briefly outline the HLM type of model we have used to study possible signals of grand unification.

Particle	$\text{SU}(2)_{\text{L}} \times \text{U}(1)_{\text{Y}} \times \text{SU}(3)_{\text{c}}$	S_4
Quarks Q	$(2, +\frac{1}{3}, 3)$	$\mathbf{3}_2$
Anti quarks u^c	$(1, -\frac{4}{3}, \bar{3})$	$\mathbf{3}_2$
Anti quarks d^c	$(1, +\frac{2}{3}, \bar{3})$	$\mathbf{3}_2$
Leptons L	$(2, -1, 1)$	$\mathbf{3}_2$
Antileptons e^c	$(1, +2, 1)$	$\mathbf{3}_2$
Right-handed ν 's	$(1, 0, 1)$	$\mathbf{3}_2$
Doublet Higgs ϕ_0	$(2, -1, 1)$	$\mathbf{1}_1$
Doublet Higgs (ϕ_1, ϕ_2)	$(2, -1, 1)$	$\mathbf{2}$
Doublet Higgs (ξ_1, ξ_2, ξ_3)	$(2, -1, 1)$	$\mathbf{3}_1$

Table 1: The minimal particle content and transformation properties in the $\mathbf{G}_{213} \times \mathbf{S}_4$ model used in Ref. [10].

In the non-Abelian discrete symmetry group S_4 , there are two types of triplet representations, $\mathbf{3}_1$ and $\mathbf{3}_2$, and also two types of singlet representations, $\mathbf{1}_1$ and $\mathbf{1}_2$, but there is only one type of doublet representation, $\mathbf{2}$. If one wishes to identify the fermions further in the fundamental representations of continuous flavor groups like $\mathbf{SO}(3)_{\text{f}}$ or $\mathbf{SU}(3)_{\text{f}}$, then the three generations of standard fermions are to transform as $\mathbf{3}_2$, rather than $\mathbf{3}_1$ of \mathbf{S}_4 . The HLM [10] proposal gives a very interesting possibility of embedding in the most attractive grand unified theory like $SO(10)$ by appending it with the continuous flavor group $\mathbf{G}_{\text{f}} = \mathbf{SO}(3)_{\text{f}}, \mathbf{SU}(3)_{\text{f}}$ in addition to S_4 . By fixing the Yukawa couplings to be symmetric in flavor space, the allowed $\mathbf{SO}(10)$ Higgs representations are $\mathbf{10}_H$'s and $\overline{\mathbf{126}}_{\text{H}}$'s. The sextplet of \mathbf{S}_4 doublet Higgs representations are appropriately fitted into those of \mathbf{G}_{f} by using six 10_H -plets of $\mathbf{SO}(10)$ with transformation property $(\mathbf{10}_{\text{H}}, \mathbf{3}_1 + \mathbf{2} + \mathbf{1}_1)$ under $\mathbf{SO}(10) \times \mathbf{S}_4$. In the minimal choice to create large right-handed Majorana neutrino mass term to drive the type-I see-saw mechanism, one additional Higgs representation transforming as $(\overline{\mathbf{126}}_{\text{H}}, \mathbf{1})$ under this group is needed [21]. However in order to generate different masses of down quarks and charged leptons, five more $\overline{\mathbf{126}}_{\text{H}}$'s may be needed. Near the S_4 breaking scale, the model consists of three generations of fermions all transforming as $\mathbf{3}_2$ and six SM-like Higgs fields transforming as $\mathbf{1}_1 + \mathbf{2} + \mathbf{3}_1$ under \mathbf{S}_4 . The particle content is summarized in Table 1.

Fermion masses and mixings in the model have been derived through a $\mathbf{G}_{213} \times \mathbf{S}_4$ invariant Yukawa Lagrangian explicitly given in ref. [10]. Although there are twelve Yukawa couplings in the $G_{213} \times S_4$ model, when embedded in a GUT like $\mathbf{SO}(10) \times \mathbf{S}_4$ they are expected to reduce to only three corresponding to three of its representations $(\mathbf{10}_{\text{H}}, \mathbf{1}_1)$, $(\mathbf{10}_{\text{H}}, \mathbf{2})$ and $(\mathbf{10}_{\text{H}}, \mathbf{3}_1)$. These three are expected to reduce to only one if the discrete flavor symmetry group emerges from continuous flavor group $G_{\text{f}} = SO(3)_F, SU(3)_f$. Although some of the CKM-quark mixings have been found to be somewhat smaller than the experimental values, in two numerical examples, the charged fermion masses have been shown to arise as small deviations from well known rank one matrices.

Although the model has the potentiality to accommodate type-II seesaw [22], the $SU(2)_L$ Higgs triplets contained in $(\overline{126}_H, 1)$ are excluded to reduce the number of parameters. The right-handed (RH) Majorana neutrino mass matrix generated by $(\overline{126}_H, 1)$ is proportional to 3×3 unit matrix in the generation space which drives the type-I see-saw formula for light neutrino masses [21, 22] and the HLM model requires the quasi-degenerate RH neutrino mass scale to be $M_R \simeq 10^{13}$ GeV. Thus the model has high potentiality to explain baryon asymmetry of the universe through resonant leptogenesis and in non-SUSY models there is no gravitino constraint [23].

Although spontaneous S_4 breaking scale in the HLM model has been assumed to be near the electroweak scale, suppression of flavor-changing neutral current (FCNC) may require all non-standard Higgs doublet masses to be $\sim O(\text{TeV})$ or larger. In that case using RG-extrapolated values of fermion masses and mixings [17] HLM-type of analysis can be carried out in the $G_{213} \times S_4$ model with spontaneous S_4 breaking at $\mu \sim O(1 - 10)$ TeV leading to the SM with only one light Higgs doublet at lower scales. Fits to the extrapolated values of masses and mixings have been carried out at $\mu = 10^{13} - 10^{15}$ GeV in [11, 12, 13, 24] and in a number of other models. Also since the extrapolation is to be done to a scale which is only $\sim 1 - 2$ order larger than the electro-weak scale, the numerical results are expected to be similar to the HLM fit with small differences. In any case for studying grand unification and capturing new signals for low-scale physics, no numerical inputs from fits to fermion masses and mixings are needed either from the HLM model [10] or from its possible type with $(1 - 10)$ TeV S_4 symmetry breaking scale.

In what follows for the purpose of embedding the HLM type model in $SO(10) \times G_f$ we will assume that $G_{213} \times S_4$ symmetry breaks to SM softly or spontaneously at $\mu = M_S \sim (1 - 10)$ TeV leading to the SM with only the standard Higgs doublet below the TeV scale.

3 Unification through single-step breaking and matter parity conservation

While implementing coupling unification, another purpose of the present work is to identify particles with $\sim \text{TeV}$ scale masses as signals of grand unification which may be cold dark matter (CDM) candidates of the universe [19, 18, 20] or other nonstandard particles accessible to collider searches. The origin of discrete symmetry existing in $SM \times S_4$ model or in the SM itself which ensures DM stability is discussed below.

3.1 Matter parity conservation in $SO(10) \times G_f$ breaking

It has been known for quite some time that matter parity is a discrete symmetry of the standard model [25],

$$P_M = (-1)^{3(B-L)},$$

where $B(L)$ is the baryon(lepton) number. $(B - L)$ is an element of gauge transformation in $SO(10)$ and it is the 15th generator of Pati-Salam color-gauge group $SU(4)_C$. Also when $SO(10) \rightarrow SU(5) \times U(1)_\chi \rightarrow SM$, $\chi = 4T_{3R} + 3(B - L)$ and since $4T_{3R}$ is always even, the χ -parity, $P_\chi = (-1)^\chi = P_M$. Matter parity survives as a discrete symmetry provided the symmetry breaking of $SO(10)$ to the SM undergoes through Higgs scalars carrying even $(B - L)$ which explains tiny left-handed (LH) neutrino masses through type-I seesaw mechanism. The survival of matter parity as a discrete symmetry in the SM also follows from general arguments for even $B - L$ [26, 27]. The vacuum expectation value (VEV) of the right-handed (RH) Higgs triplet carrying $(B-L) = -2$ is contained in $(\overline{126}_H, 1)$ of $SO(10) \times G_f$. This has been utilized in one-step or two-step breaking models discussed throughout this work to ensure survival of matter parity. In $SO(10)$, for dimension of representations ≤ 210 , while the representation 16 and 144 have odd P_M , the matter parity of representations 10, 45, 54, 120, 126, $\overline{126}$, and 210 is even. Utilizing this property and, as necessary requirement of gauge coupling unification, non-standard Higgs scalars (singlet and neutral component of weak doublet) in 16_H [18] or neutral component of non-standard weak triplet fermion contained in 45_F [20] have been identified as possible DM candidates. While a fermionic color-octet has been also found necessary for coupling unification in [20], it can never be directly observed at accelerator energies because the predicted value of its mass is large (7×10^{10} GeV). In contrast, while searching for completion of grand unification in the presence of flavor symmetry, it will be shown in this work that both the triplet DM and the color-octet fermion with \sim TeV scale masses are signaled by grand unification and, as such, both are accessible to the ongoing or planned accelerator searches.

3.2 Absence of unification in the minimal model

In this section we search for gauge coupling unification of the HLM type model with six electroweak doublets belonging to the \mathbf{S}_4 representations $(\mathbf{3}_1 + \mathbf{2} + \mathbf{1}_1)$. We assume the symmetry $\mathbf{G}_{213} \times \mathbf{S}_4$ to be restored at $\mu = M_S \sim (1-10)$ TeV and, thereafter, to continue till $SO(10) \times G_f$ symmetry takes over at the GUT scale $\mu = M_U \gtrsim 10^{15}$ GeV with no intermediate gauge symmetry. Between the scales M_Z and M_S , the standard model symmetry with one Higgs doublet is assumed to operate. For this Model I we consider

$$SO(10) \times \mathbf{G}_f \xrightarrow{M_U} \mathbf{G}_{213} \times \mathbf{S}_4 \xrightarrow{M_S} \mathbf{G}_{213}. \quad (1)$$

where we give GUT-scale vacuum expectation values (VEVs) to the relevant components of Higgs representations $(54_H, 1) \oplus (45_H, 1) \oplus (\overline{126}_H, 1)$ under $SO(10) \times G_f$ in the first step of symmetry breaking. The second and subsequent steps proceed in a similar manner as explained in [10]. For the evolution of gauge couplings we utilize the two-loop renormalization group equations [28, 29],

$$\frac{d\alpha_i}{dt} = \frac{a_i}{2\pi} \alpha_i^2 + \sum_j \frac{b_{ij}}{8\pi^2} \alpha_i^2 \alpha_j. \quad (2)$$

In our notation a_i ($i = 1, 2, 3$) denote one-loop beta function coefficients for the fine-structure constants of $U(1)_Y$, $SU(2)_L$ and $SU(3)_C$, respectively, and b_{ij} , ($i, j = 1, 2, 3$) denote the corresponding two-loop coefficients as elements of a 3×3 matrix. Noting that $a_i = (41/10, -19/6, -7)$ for the SM with one doublet, but $a_i = (23/5, -7/3, -7)$ in the $G_{213} \times S_4$ model with six doublets, we have used the Particle-Data-Group values[30] of $\sin^2 \theta_W(M_Z) = 0.23116 \pm 0.00013$ and $\alpha^{-1}(M_Z) = 127.9$. In order to make the point more convincing on whether unification is taking place in the minimal model, we have chosen 3σ deviation from the global average of the strong interaction coupling, $\alpha_S(M_Z) = 0.1184 \pm 0.0007$, so that, statistically, our result would be valid at 99.7% confidence level. The evolutions of the three gauge coupling-constants from $\mu = M_Z$ to $\mu = M_{\text{Planck}}$ is shown in Fig. 1 where the widths of electroweak lines are at 1σ but the width of strong-interaction coupling is at 3σ .

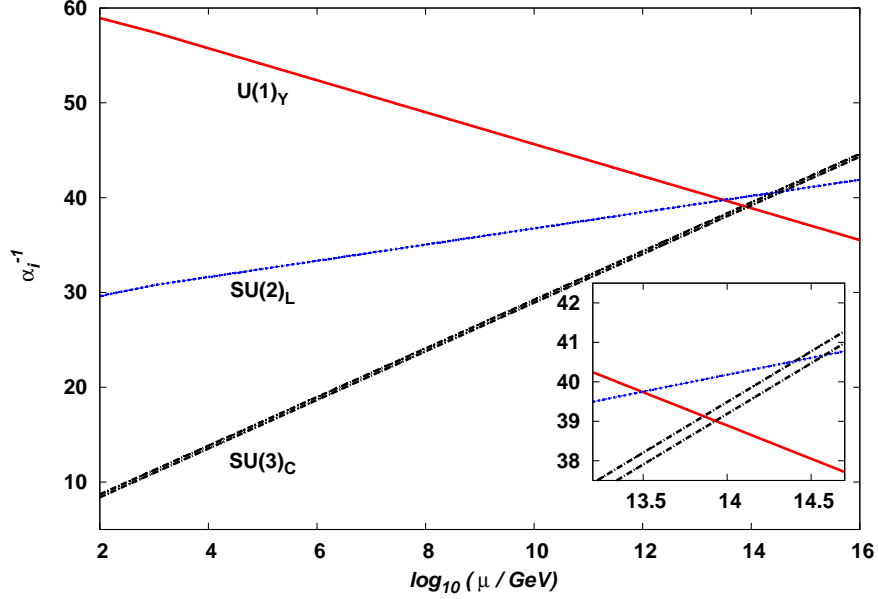


Figure 1: RG evolutions of three gauge couplings of the standard model from $\mu = M_Z$ to $\mu = M_{\text{Planck}}$ with $M_S \simeq 1$ TeV where $\alpha_S(M_Z)$ has been used with 3σ uncertainty and others with 1σ uncertainty. The inset in the figure shows the presence of the triangular region at the high scale where the two dot-dashed parallel lines represent the 3σ boundaries of $\alpha_S^{-1}(M_Z)$.

When the S_4 spontaneous breaking scale is changed from $M_S = 1$ TeV to 10 TeV there is no significant change of the triangular region. In particular when this scale becomes large with $M_S \simeq 10^{14}$ GeV, the triangular structure of the minimal non-SUSY SM appears exhibiting the well known deconstructed unification. Although the size of the triangle appears to be smaller when the 3σ error bar in $\alpha_S(M_Z)$ is taken into account, the non-overlapping region is prominent to show that the inverse fine structure constants cross at three different points. Evidently there is no possibility of gauge coupling unification with the minimal particle content of the $G_{213} \times S_4$ model.

3.3 Unification with fermionic triplet dark matter and color-octet fermion

It has been shown in a number of investigations in the absence of flavor symmetry in supersymmetric as well as non-supersymmetric models, with or without intermediate symmetry, that grand unification of gauge couplings at $M_U \geq 10^{15}$ GeV is achieved provided there are additional particle degrees of freedom (scalars or fermions) at lower scales [18, 20, 31, 32, 33, 34, 35, 36, 23]. The light scalars needed for completion of grand unification require additional fine tuning and the criteria of minimal fine tuning [37] are to be relaxed. As we are discussing unification along with flavor group through $SO(10) \times G_f$, there is also the possibility that a single additional fine tuning that would have made one submultiplet of a GUT-representation light without flavor symmetry, would now make a n-tuple of G_f light. On the other hand if unification is achieved with non-standard light fermions, there may be a global $U(1)$ symmetry to protect their masses and the fine-tuning may not be so unnatural. Although finally we achieve unification with light fermions only, we start with light scalars.

Using one-loop and two-loop coefficients in different mass ranges we find unification is possible with a pair of color-octet scalars $2C(1, 0, 8)$, and a pair of weak triplet scalars $2\sigma(3, 0, 1)$, with both the masses near the TeV scale and a GUT scale suitable to guarantee observed proton stability ¹

$$\begin{aligned} M_S &= 10^{2.5} \text{ GeV}, \quad M_X = M_\sigma(3, 0, 1) = 10^3 \text{ GeV}, \\ M_C(1, 0, 8) &= 10^{3.5} \text{ GeV}, \quad M_U = 10^{16} \text{ GeV}, \quad 1/\alpha_G = 35.3. \end{aligned} \quad (3)$$

For this model almost exact unification of the three gauge couplings is shown Fig.2.

In this Model I, the pairs of Higgs scalars $2C(1, 0, 8)$ and $2\sigma(3, 0, 1)$ can be embedded into $(210_H, 2)$, or $(45_H, 2)$ under $SO(10) \times S_4$, or into the representation $(24_H, 2)$ under $SU(5) \times S_4$.

Purely from the requirement of coupling unification, this leads to an interesting possibility of replacing each pair by the corresponding fermions, $F_\sigma(3, 0, 1)$ and $F_C(1, 0, 8)$ at the same scale. The simple reason for this possible replacement is that the one-loop beta function coefficient remains the same as the scalar case leading to almost the same pattern of unification as in Fig.2. The fermionic weak-triplet at the TeV scale which is a color singlet and has hypercharge $Y=0$ can be identified as a dark matter candidate if it does not have Yukawa interaction with standard model particles.

These results arrived through numerical analyzes have a simple analytic derivation. Analyzed in a straight-forward manner, the above results turn out to be automatic predictions of the $G_{213} \times S_4$ model with six doublets. The proof proceeds through the following steps. The

¹We have checked that solutions to coupling unification obtained in all cases discussed in this paper can also be obtained if the S_4 symmetry breaking scale is larger, 1-10 TeV, needed to avoid more than one Higgs doublets at lower scales, suppress FCNC effects and Higgs search prospects at Tevatron and LHC.

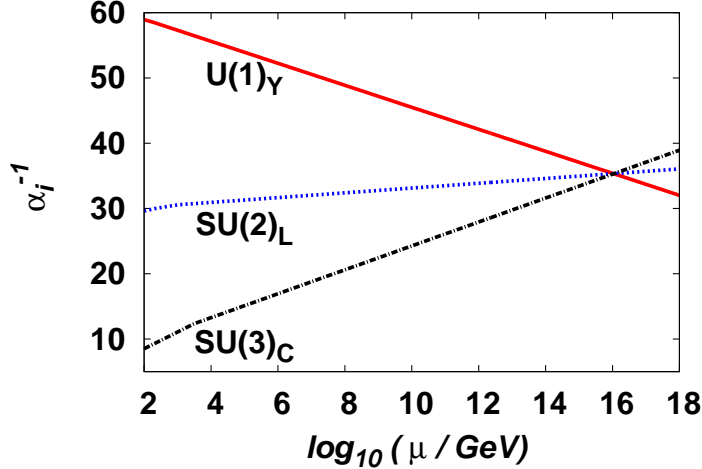


Figure 2: Unification of gauge couplings in single-step breaking Model-I with scalars $2\sigma(3, 0, 1)$ and $2C(1, 0, 8)$ at $M_\sigma \simeq 1$ TeV and $M_C \simeq 3$ TeV, respectively. The unification pattern is unchanged when all the four scalars are replaced by fermions $F_\sigma(3, 0, 1)$ and $F_C(1, 0, 8)$ at the respective scales.

first observation is that, with respect to one-loop contributions to gauge couplings, the six doublets are equivalent to two Higgs doublets and their superpartners of the MSSM. The second observation is the well known fact that the scalar superpartners of quarks and leptons do not determine the MSSM GUT scale although they contribute to the value of the GUT gauge coupling. Using these two observations, it immediately follows that there are only the following nontrivial degrees of freedom missing from the low-mass non-SUSY spectrum to match the MSSM spectrum sans squarks and sleptons: the octet fermion and the triplet fermionic DM. When these degrees of freedom are included in the non-SUSY model near the TeV scale, it predicts grand unification of gauge couplings with the non-SUSY GUT scale identical to the MSSM-GUT scale ($\simeq 10^{16}$ GeV)[38]. Both the GUT scale and the predicted low-mass particles are specific to this non-SUSY six-Higgs doublet model which have been also obtained by independent numerical analyzes stated above.

Noting that the quantum numbers of the weak-triplet and the color octet match the corresponding components of the adjoint representation, we suggest that these fermions are lighter components of the non-standard fermionic representations $(45_F, 1) \subset SO(10) \times S_4$. As this representation has even matter parity, it does not couple to standard model fermions or the Higgs scalar directly, although there could be matter-parity conserving non-standard Yukawa interaction which has been discussed in Sec.4 in some model extensions. Even in the $SO(10)$ theory itself 45_F does not have usual Yukawa interaction with standard fermions in 16_F through SM Higgs doublets which might originate from 10_H , $\overline{126}_H$, and 120_H or their linear combinations.

It is worthwhile to compare fermionic signals of grand unification between the conventional $SO(10)$ [20] and the present model. In the $SO(10)$ model in addition to the triplet fermionic

dark matter near the TeV scale, a color-octet fermion with mass 7×10^{10} GeV was also needed to complete grand unification. Because of the high mass it appears impossible to testify the presence of such a fermion at accelerator energies. In the present model, apart from components of additional Higgs doublets with masses $\sim \text{few TeV} - 10 \text{ TeV}$, which are natural ingredients of the model, completion of grand unification predicts both the triplet fermionic dark matter as well as the color-octet fermion with $\sim \text{TeV}$ scale masses; as such they are subject to verification at accelerator energies. In Sec.4 we will discuss some phenomenological consequences of these light fermions while we derive their TeV scale masses using renormalizable Yukawa Lagrangian of $(45_F, 1) \subset SO(10) \times G_f$.

Neutrino masses and mixings being governed by the type-I see-saw mechanism, the RH neutrino mass matrix is proportional to a diagonal matrix. As $(\overline{126}_H, 1)$ generates the RH neutrino mass via its coupling $f 16_f 16_f \overline{126}_H$, and the vacuum expectation value $\langle \overline{126}_H \rangle \sim M_{GUT}$, it is necessary that the Majorana type Yukawa coupling $f \simeq 10^{-3}$ in Model I. In the next subsection we estimate proton lifetime predictions in this model by including uncertainties due to GUT-threshold as well as low-scale threshold effects [39, 40, 41, 42] in order to have an approximate idea of the allowed range for experimental accessibility.

3.4 Predictions on proton lifetime

In $SU(5)$ model the $d = 6$ proton decay operator emerges from 12 superheavy gauge bosons contained in $(2, -\frac{5}{3}, 3) \oplus (2, \frac{5}{3}, \overline{3})$ under G_{213} . In $SO(10)$ the superheavy gauge bosons transform simultaneously as LH and RH doublets and are contained in the $(2, 2, 6)$ multiplet under Pati-Salam group G_{224} . Up to a good approximation, the decay width for $p \rightarrow e^+ \pi^0$ in all models investigated in this work can be written as [35, 43, 23]

$$\begin{aligned} \Gamma(p \rightarrow e^+ \pi^0) &= \frac{m_p}{64\pi f_\pi^2} \left(\frac{g_G^4}{M_U^4} \right) A_L^2 \bar{\alpha}_H^2 (1 + D + F)^2 [(A_{SR}^2 + A_{SL}^2) \\ &\times (1 + |V_{ud}|^2)^2] \end{aligned} \quad (4)$$

In eq.(4) M_U represents degenerate mass of 24 superheavy gauge bosons and g_G is their coupling to quarks and leptons ($\alpha_G = g_G^2/4\pi$) at the GUT scale $\mu = M_U$. Here $\bar{\alpha}_H$ = hadronic matrix elements, m_p = proton mass = 938.3 MeV, f_π = pion decay constant = 139 MeV, and the chiral Lagrangian parameters are $D=0.81$ and $F=0.47$. V_{ud} represents the CKM- matrix element $(V_{CKM})_{12}$ for quark mixings.

The dimension 6 operator when evolved down to the GeV scale, short-distance renormalization factor from $\mu = M_U - M_Z$ turns out to be $A_{SL} \simeq A_{SR} \simeq A_{SD} \simeq 2.566$ for Model I and the long distance renormalization factor is $A_L \simeq 1.25$. These are estimated using values of gauge couplings in the relevant mass ranges, the anomalous dimensions and the one-loop beta-function coefficients [44]. Using $A_R = A_L A_{SD} \simeq 3.20$, $F_q = 2(1 + |V_{ud}|^2)^2 \simeq 7.6$, we express inverse decay width for $p \rightarrow e^+ \pi^0$ as

$$\begin{aligned}\Gamma^{-1}(p \rightarrow e^+ \pi^0) &= 1.01 \times 10^{34} yrs. \left[\frac{0.012 \text{ GeV}^3}{\alpha_H} \right]^2 \left[\frac{3.2}{A_R} \right]^2 \\ &\times \left[\frac{1/35.3}{\alpha_G} \right]^2 \left[\frac{7.6}{F_q} \right] \left[\frac{M_U}{4.659 \times 10^{15}} \right]^4.\end{aligned}\quad (5)$$

where we have used $\alpha_H = \bar{\alpha}_H(1+D+F) \simeq 0.012 \text{ GeV}^3$ from recent lattice theory estimations[45].

Using the two-loop estimations of Model I with $M_U = M_U^0 = 10^{16} \text{ GeV}$ in eq.(5) gives

$$\tau_p^0 = 2.48 \times 10^{35} \text{ yrs.} \quad (6)$$

which is nearly 25 times longer than the current experimental limit, but accessible to measurements by next generation proton decay searches.

3.5 Threshold effects

We have found that completion of grand unification requires a pair of weak-triplet scalars and a pair of color-octet scalars with masses near the TeV scale which could be members of S_4 -doublets. Alternatively, the same unification is completed by fermionic weak-triplet as a prospective DM candidate and a fermionic color-octet, both with $\sim \text{TeV}$ scale masses. The origin of these additional low-mass scalars may be attributed to the adjoint representations $(45_H, 2)$, or equivalently, the low-mass fermions may originate from $(45_F, 1)$ under $SO(10) \times G_f$. Although the representations $54_{F,H}$ or $210_{F,H}$ may be chosen instead of $45_{F,H}$, we prefer to choose the the smallest representation among the three. We find that contributions of superheavy components of $(45_{F,H})$ towards GUT-threshold correction on unification mass vanishes and its possible reason has been explained [46]. Including the GUT-threshold effects of non-degenerate² superheavy components in $\overline{126}_H$ and $6(10_H)$, and low-scale M_S - threshold effects due to six light Higgs doublets treated as degenerate, the maximal uncertainties on the unification mass and proton lifetime are [39, 40, 41],

$$\frac{M_U}{M_U^0} = 10^{\pm 0.0465|\eta| \pm 0.031|\eta'|}, \quad (7)$$

where $\eta = \ln(M_{SH}/M_U)$, M_{SH} being the scale of superheavy masses lighter or heavier than the GUT-scale. It characterizes splitting of masses around M_U . Here $\eta' = \ln(M_D/M_S)$, M_D being

²This non-degeneracy is not the same as in the conventional sense. In this and all other models, we have assumed that all superheavy sub-multiplets belonging to any particular GUT representation are degenerate in mass whereas there could be non-degeneracy among masses assigned to different GUT representations.

the common mass of degenerate doublets around M_S - threshold. We have noted that maximal contribution to uncertainty due to M_S - threshold occurs when the doublets are degenerate.

Using eq.(6) and eq.(7), we find that even for non-degenerate superheavy component masses $10(\frac{1}{10})$ times heavier(lighter) than the GUT-scale corresponding to $|\eta| = \ln(10)$ and M_S - threshold parameter $|\eta'| = \ln(5)$, the predicted proton lifetime is

$$\tau_p = 10^{35.245 \pm 0.428 \pm 0.2} \text{ yrs}, \quad (8)$$

which is in the accessible range of planned searches [8].

4 Masses of non-standard fermions and phenomenology

We have noted that a weak triplet fermion $F_\sigma(3, 0, 1)$ and a color-octet fermion $F_C(1, 0, 8)$ with \sim TeV scale masses are predicted by flavor-symmetric grand unification in single-step breaking Model I. The presence of such low mass fermions may not be as unnatural since, in the limiting case of their vanishing masses, they may be protected by corresponding $U(1)$ global symmetry. In this section, using $SO(10) \times G_f$ theory, we show how they can be light and briefly discuss their phenomenology. We introduce the adjoint fermion representation $A_F = (45_F, 1)$ and the Higgs representations $E(54_H, 1)$ and $\Phi(210_H, 1)$ under $SO(10) \times G_f$ and consider the renormalizable Yukawa Lagrangian at the GUT scale,

$$-L_{Yuk} = A_F (m_A + h_p \Phi + h_e E) A_F.$$

with $m_A \simeq M_U$. While E has only one singlet, Φ has three singlets $\Phi_i (i = 1, 2, 3)$ under SM. When GUT-scale VEVs are assigned to E and Φ along these directions, besides the GUT symmetry breaking, the fermion components in A_F get masses [47],

$$\begin{aligned} m(1, 2/3, 3) &= m_A + \sqrt{2}h_p \frac{\Phi_2}{3} - 2h_e \frac{\langle E \rangle}{\sqrt{15}}, \\ m(2, 1/6, 3) &= m_A + h_p \frac{\Phi_3}{3} + h_e \frac{\langle E \rangle}{2\sqrt{15}}, \\ m(2, -5/6, 3) &= m_A - h_p \frac{\Phi_3}{3} + h_e \frac{\langle E \rangle}{2\sqrt{15}}, \\ m(1, 1, 1) &= m_A + \sqrt{2}h_p \frac{\Phi_1}{\sqrt{3}} + \sqrt{3}h_e \frac{\langle E \rangle}{\sqrt{5}}, \\ m(1, 0, 1) &= m_A + \sqrt{2/3}h_p \Phi_1 + \sqrt{3/5}h_e \langle E \rangle, \\ m'(1, 0, 1) &= m_A + \frac{2\sqrt{2}}{3}h_p \Phi_2 - \frac{2}{\sqrt{15}}h_e \langle E \rangle, \\ m_{F_C}(1, 0, 8) &= m_A - \frac{\sqrt{2}}{3}h_p \Phi_2 - \frac{2}{\sqrt{15}}h_e \langle E \rangle, \end{aligned}$$

$$m_{F_\sigma}(3, 0, 1) = m_A - \sqrt{\frac{2}{3}}h_p\Phi_1 + \sqrt{\frac{3}{5}}h_e < E > .$$

It is clear that by tuning any two of the parameters while the weak triplet and color-octet fermion masses, $m_{F_\sigma}(1, 3, 0)$ and $m_{F_C}(1, 0, 8)$, are brought to the \sim TeV scale, all other components have masses near the GUT scale. These two fermions are analogous to wino and gluino of split-SUSY models where the scalar superpartners have very large masses [48]. Although from the minimality of the dimension of representation, we have chosen $(45_F, 1)$ as the possible origin of the two light fermionic submultiplets, alternatively, $(54_F, 1)$ or $(210_F, 1)$ may be chosen with similar derivation.

(i) Weak-triplet fermionic dark-matter

The decay of the heavier charged components F_σ^\pm to the lighter neutral component via weak-gauge interaction leads to the mass difference $m_{F_\sigma^\pm} - m_{F_\sigma^0} = 166$ MeV [19, 49]. Within 3σ uncertainty of the WMAP data on relic density its mass has been estimated as $m_{F_\sigma} = 2.75 \pm 0.15$ TeV corresponding to the Sommerfeld resonance value at 2.5 TeV [19, 50]. In a more recent analysis, taking into account the effect of kinetic decoupling, the Sommerfeld resonant value has been found to be the same as the triplet mass $m_{F_\sigma} \simeq 4.5$ TeV [51].

Elastic scattering of DM off the nucleon occurs through the loop-mediated W-boson exchange with and without the SM Higgs boson and leads to a suppressed spin-independent cross section [19]. Although this cross section is 2–3 orders of magnitude lower than the current experimental sensitivities, it is expected to be within the accessible range of planned experiments for direct detection [52]. The large mass splitting between the charged and neutral components of the triplet ($\simeq 166$ MeV) compared to the proton-neutron mass difference or the DM kinetic energy, kinematically forbids inelastic scattering.

For indirect detection, DM pair annihilation and resulting fluxes of photons, antiprotons, and positrons, diffuse or from the center of Milky-Way galaxy, have been predicted [19, 50, 53, 51]. Because of the proximity of the highly nonrelativistic triplet mass to the Sommerfeld resonant value, the DM-annihilations are boosted resulting in enhancement by a factor as large as $\sim O(100)$. The recent estimation with $m_{F_\sigma} \simeq 4.5$ TeV has explained the observed PAMELA excess of positrons [54] boosted by Sommerfeld resonance effect. The anti-proton flux prediction agrees well with the present measurement even up to energies ≤ 200 GeV [55]; but a clear trend of this boosted flux is predicted in the region of 300 – 1000 GeV in which no experimental data are yet available [51].

Experiments using atmospheric Cherenkov telescopes expect to observe monochromatic photons with energy $\simeq m_{F_\sigma}$ which originate from pair annihilation $F_\sigma \bar{F}_\sigma \rightarrow \gamma\gamma$ [50, 53]. Observation of such photons would determine the triplet mass but non-observation would rule out the triplet-DM model. More recent analysis of first two years of Fermi Gamma Ray Space Telescope data from galactic center have been found to fit a low mass DM particle in the range 7 – 10 GeV. [56].

The 2.75 TeV triplet DM production rate for direct detection at colliders has been estimated to be $\sim 10^{-45}$ cm² which is accessible with improved accelerator energy and luminosity. With

LHC luminosity of 100 fb^{-1} , the $pp \rightarrow F_\sigma^+ F_\sigma^- X$ cross section has been predicted to produce only one DM pair [19]. On the other hand, if a hadronic collider is available with twice the LHC energy, then it will have production cross section and produced number of DM pairs several orders of magnitude larger. In e^+e^- collider with energy $\simeq 5.5 - 8 \text{ TeV}$, observation of $F_\sigma^+ F_\sigma^-$ pair is possible through Z-exchange at tree level while $F_\sigma^0 \bar{F}_\sigma^0$ pair production is allowed at loop level. After production it may be easier to identify the charged component of the triplet as it is predicted to leave long lived tracks corresponding to the estimated lifetime of $\simeq 5.5 \text{ cm}$. The alternative possibility with a large mass (4.5 TeV) for the triplet appears to cause problem for direct production and detection at LHC energies. However, if the phenomenon of cold dark matter originates from more than one components including the triplet, then the triplet mass may be smaller and easier for collider signatures but at the cost of predictive power of the model.

(ii) Color-octet fermion

In Model I, in addition to the fermionic weak-triplet, completion of gauge coupling unification has been found to require the presence of color-octet fermion $F_C(1, 0, 8)$ or, equivalently, a pair of color-octet scalars $C(1, 0, 8)$ and we have suggested their possible origins from the adjoint representations $(45_F, 1)$ or $(45_H, 2)$ of $SO(10) \times G_f$. Here at first we discuss briefly the more interesting case of the color-octet fermion. Consistent gauge coupling unification in Model I is noted to be possible for rather a wider mass range of the color-octet fermions $m_{F_C}(1, 0, 8) = 500 \text{ GeV} - 10 \text{ TeV}$.

Being hadron colliders, both Tevatron and LHC are expected to show much higher rate of production of color-octets compared to color-triplets because of larger Dynkin index. The production of $F_C(1, 0, 8)$ at hadron collider would be in pairs via gluon-gluon fusion or through $q\bar{q}'$ annihilation in a manner similar to gluino pair production. In the leading order(LO) using the parton level amplitudes for $F_C \bar{F}_C$ production in the non-SUSY case via quark-antiquark annihilation or via gluon-gluon fusion [57], the parton level cross sections are,

$$\begin{aligned}\hat{\sigma}(q\bar{q}' \rightarrow F_C \bar{F}_C) &= \frac{8\pi\alpha_S^2}{9\hat{s}}[(1 + \kappa/2)(1 - \kappa)^{1/2}], \\ \hat{\sigma}(gg \rightarrow F_C \bar{F}_C) &= \frac{9\pi\alpha_S^2}{32\hat{s}}[(8 + 4\kappa + 2\kappa^2) \ln \frac{1 + (1 - \kappa)^{1/2}}{1 - (1 - \kappa)^{1/2}} - \frac{2}{3}(16 + 17\kappa)(1 - \kappa)^{1/2}].\end{aligned}\quad (9)$$

where \hat{s} = partonic c.m. energy squared and $\kappa = 4m_{F_C}^2/\hat{s} \leq 1$.

Using CTEQ6 parton density distribution function [58] and integrating, we obtain the total pair production cross section $\sigma(\text{pb})$ at LHC energy of $\sqrt{s} = 14 \text{ TeV}$ and the number(N) of $F_C \bar{F}_C$ pairs produced for different values of color-octet fermion masses,

$$\begin{aligned}\sigma(\text{pb}) &= 0.9, & 1.0 \times 10^{-2}, & 1.5 \times 10^{-4}, & 2.5 \times 10^{-5}, \\ N &= 9 \times 10^4, & 1 \times 10^3, & 15, & 2.5,\end{aligned}$$

$$m_{F_C}(\text{TeV}) = 1.0, \quad 2.0, \quad 3.0, \quad 3.5. \quad (10)$$

where we have used the beam luminosity of 100 fb^{-1} . These cross sections are nearly 10 times larger than the heavy-quark pair production cross section. It is clear that even though the cross section decreases rapidly with increasing fermion mass, the number of pairs produced are $9 \times 10^4(1000)$ even for $m_{F_C} \simeq 1(2) \text{ TeV}$.

Even though the pair production cross section of non-SUSY color-octet fermions is large, unlike gluinos[59], their decays would be suppressed in the present minimal Model I. This is because $(45_F, 1)$ does not have renormalizable Yukawa type interaction with fermions or Higgs doublets of $G_{213} \times S_4$ model. Also there are no analogue of superpartners in this non-SUSY model. Having its origin in the adjoint representation, being neutral under $SU(2)_L \times U(1)_Y$, and in the absence of Yukawa interaction, the color-octet fermion interacts with quarks at the tree level only via gluon exchange by which it can hadronize. However, the color-octet fermions may decay into standard model fermions and one of the light members of $(45_F, 1)$ via higher-dimensional-operator-mediated effective interactions whose strength depends upon possible presence of scalars with high masses giving rise to the operator in some minimally extended models. With appropriately longer lifetime, the produced color-octet fermions may decay outside the detector or with displaced vertices, or some of them may be even stopped in the detector. Even if no superpartners are present, they may also form some states, analogous to R-hadrons[48, 60, 61]. These possibilities would be explored separately and an extended model may mimic split- SUSY model [48] to some extent with more interesting collider signatures driven by color-octet fermions. It is clear that at the highest LHC energy and a 100 fb^{-1} luminosity, detection of color-octet pair production would be possible at least up to the particle mass $\sim 3500 \text{ GeV}$.

One of the major goals of LHC and Tevatron is to resolve the issue of supersymmetry through collider signatures of superpartners and definite answers in this respect are expected in the next few years. In the context of the present flavor symmetric grand unified Model I even without inclusion of additional GUT representations, collider signature of the color-octet fermion would be large production cross section and absence of superpartners.

Two important issues related to the $\sim \text{TeV}$ mass color-octet fermions are their lifetime and relic abundance. Both these are dependent upon the mass $M_{\text{med.}}$ of the scalar mediators contained in $\overline{16}_H \subset SO(10)$ generating the effective four-fermion interactions via matter-parity conserving Yukawa interaction, $Y 45_F 16_F \overline{16}_H$ where S_4 quantum numbers have been suppressed and our models have now been minimally extended to include the Higgs representation $(\overline{16}_H, 3) \subset SO(10) \times S_4$. An approximate formula for the color-octet fermion lifetime is,

$$\tau_{F_C} = 3 \times 10^{-2} \text{ sec} \left(\frac{M_{\text{med.}}}{10^9 \text{ GeV}} \right)^4 \left(\frac{1 \text{ TeV}}{m_{F_C}} \right)^5 \quad (11)$$

Normally $M_{\text{med.}}$ is expected to be near the GUT-scale or few-orders lighter as in Model I,

although in Model II it can be even lighter. However, we note that the $SU(5)$ -complete multiplets like $\overline{10}_H$ or 5_H contained in $\overline{16}_H \subset SO(10)$ can be made light with any value of $M_{\text{med.}} \simeq 10^4 \text{ GeV} - 10^{16} \text{ GeV}$ without affecting coupling unification and the GUT-scale ($\sim 10^{16} \text{ GeV}$) already achieved in Model I. For example cosmologically safe short-lived color octets with life-times $10^{-20} \text{ secs} (3 \times 10^{-2} \text{ secs})$ can be easily obtained in the minimal extension of the single-step breaking model with $M_{\text{med.}} = 10^4 \text{ GeV} (10^9 \text{ GeV})$ which will be discussed elsewhere while examining collider signatures. Although introduction of these scalar mediators do not affect the value of the GUT-scale in the single-step breaking model, they would tend to increase the value of the GUT-gauge coupling by a small amount with a correspondingly small decrease in the predicted proton-lifetime by a factor $\sim (35.3\alpha'_G)^2$ where α'_G is the GUT-fine structure constant including the lighter scalar mediators as would be applicable.

For a very long-lived octet fermions with lifetime comparable to the age of the universe, or even larger, corresponding to scalar mediator masses in the range $10^{13} \text{ GeV} - 10^{16} \text{ GeV}$, extensive investigations have been made to overcome their relic density problem. Perturbatively generated larger relic density of these color-octet fermions, which may contribute to hitherto unobserved DM relic abundance [48, 62], is usually evaded by invoking second inflation at lower scale [63]. A second possibility is the substantial reduction of the octet-fermion relic density by rapid pair-annihilations that continue to temperatures much lower than the freeze-out through various nonperturbative mechanisms accompanied by Sommerfeld enhancements of the annihilation cross sections. The general conclusions are that until and unless the second inflation hypotheses are ruled out or the nonperturbative mechanisms are proved untenable, long lived octet fermions in the mass range $1 - 10 \text{ TeV}$ can be treated cosmologically safe and harmless [60].

Although Tevatron has reached the lower limit $m_{\tilde{g}} \geq 370 \text{ GeV}$ for stopped gluinos, [64], where interaction with squarks plays significant roles, no such limit is available for non-supersymmetric color-octet fermions. Similarly, for the conventional gluinos of the constrained MSSM, CMS collaboration has set the lower bound on gluino mass $m_{\tilde{g}} \geq 650 \text{ GeV}$ [65] while ATLAS collaboration has set the lower bound of 870 GeV [66], but no such high mass limit is yet available for the color-octet fermion of the non-SUSY models. Very recently a conservative lower bound on the search limit of color- octet fermion mass at $m_{F_C} \geq 50 \text{ GeV}$ has been set for LHC energy $\sqrt{s} = 7 \text{ TeV}$ [67]. Interesting suggestions have been advanced for detection of long-lived stopped gluinos with displaced vertices many of which are applicable to the case of color-octet fermions discussed in this work [61].

Pair production of color-octet scalars either through $q\bar{q}$ annihilation or through gluon-gluon fusion at Tevatron have been discussed leading to the production cross section of nearly 100 fb and 7 fb for the scalar masses 250 GeV and 350 GeV , respectively. Even though the production cross section of the color-octet scalars indicated in the present models are similar, being placed in $(45_H, 2)$, or $(54_H, 2)$, or $(210_H, 2)$ under $SO(10) \times S_4$, their interactions are somewhat different from those discussed in the literature[32, 68, 69].

5 Unification with intermediate symmetry

In the absence of flavor symmetry, whereas the single-step breaking minimal grand desert models have been ruled out, GUTs such as $SO(10)$ with one or more intermediate symmetries have been found to be consistent with $\sin^2 \theta_W$ and proton-lifetime constraints [42, 70, 71, 72]. In addition, the left-right symmetry breaking intermediate scale has been identified with type-I see-saw scale in a number of models [42, 72]. In this section using flavor unification through $SO(10) \times G_f$ at first we explore the possibility of intermediate Pati-Salam gauge theory with unbroken D-Parity [70, 72] and then summarize briefly the outcome of other intermediate symmetries.

5.1 Intermediate symmetry $SU(2)_L \times SU(2)_R \times SU(4)_C (g_{2L} = g_{2R}) \times S_4$

We consider the symmetry breaking chain

$$SO(10) \times S_4 \xrightarrow{M_U} G_{224D} \times S_4 \xrightarrow{M_R} G_{213} \times S_4. \quad (12)$$

where we have used the notation G_{224D} for $SU(2)_L \times SU(2)_R \times SU(4)_C (g_{2L} = g_{2R})$. This symmetry has the advantage that, in the presence of D-parity, exact results on vanishing corrections on $\sin^2 \theta_W$ and intermediate scale (M_R) lead to the stability of M_R [72] once it is fixed by the lower scale parameters in spite of apprehension that uncertainties on intermediate scale prediction could be large [73]. Also unlike other gauge theories, G_{224D} has only two gauge couplings which eliminates uncertainties in unification that would have otherwise arisen because of the presence of a triangular region around the GUT scale as is common to three gauge coupling models. The first step of breaking is driven assigning GUT-scale VEV to the G_{224} -singlet in $(54_H, 1) \subset SO(10) \times G_f$ and the second step is implemented through $(\overline{126}_H, 1) \oplus (45_H, 1)$ under $SO(10) \times G_f$ and the rest are as in Model I. Successful unification of couplings with proton stability and right value of the see-saw scale is possible if this Model II has any one of the three combinations of particles with masses \sim TeV: (i) a color-octet scalar, (ii) a color-octet scalar and the fermionic triplet DM, (iii) a color-octet fermion and the fermionic triplet DM. The mass parameters and the GUT-coupling in the first case are,

Model II

$$\begin{aligned} M_S &= 10^{2.5} \text{ GeV}, \quad M_X = M_C(1, 0, 8) = 10^{2.7} \text{ GeV}, \\ M_R^0 &= M_{C'}(1, 1, 15) = 10^{14.15} \text{ GeV}, \quad M_U^0 = 10^{15.6} \text{ GeV}, \quad \alpha_G^{-1} = 37.2. \end{aligned} \quad (13)$$

The RG evaluation and unification of couplings are shown in Fig.3. For the cases (ii) and (iii) the pattern of unification is similar but with different values of unification and intermediate scales: case (ii) $M_R^0 = 10^{14.6} \text{ GeV}$, $M_U^0 = 10^{15} \text{ GeV}$, $\alpha_G^{-1} = 37.1$; case (iii) $M_R^0 = 10^{15.35} \text{ GeV}$, $M_U^0 = 10^{16.9} \text{ GeV}$, $\alpha_G^{-1} = 34.6$;

Like Model I, $A_R \simeq 2.347$ in Model II in Case (i). Since the proton lifetime predicted is only a

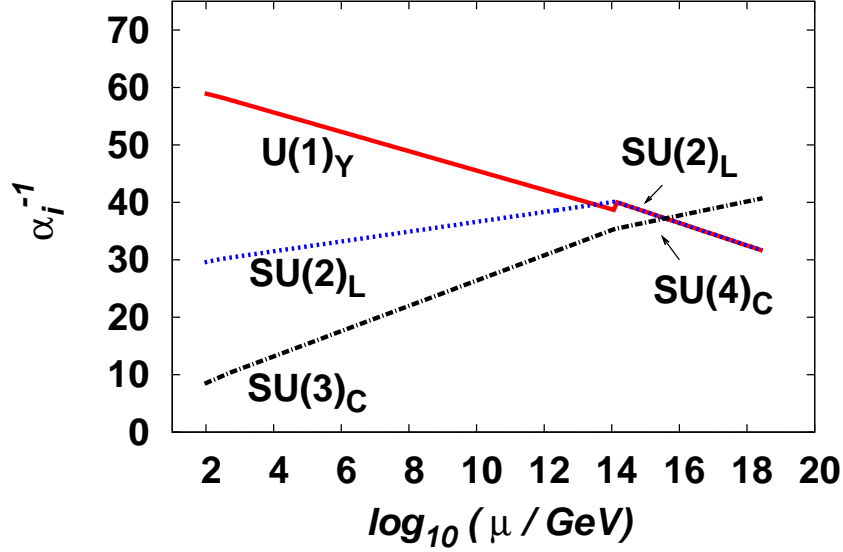


Figure 3: Unification of gauge couplings with $G_{224D} \times S_4$ intermediate symmetry shown for Model II, Case (i) with a S_4 - singlet color-octet scalar $C(1, 0, 8)$ at $M_C \simeq 500$ GeV described in the text. The unification patterns in Cases (ii) and (iii) including triplet fermionic DM and color-octet fermion or scalar is similar but with different values intermediate and GUT scales.

little shorter than the experimental lower bound ,

$$\tau_p^0 \simeq 10^{-0.3} \times (\tau_p)_{expt}. \quad (14)$$

it can be easily compensated by small threshold effects. We have checked that the M_S -threshold effects on the unification mass and proton lifetime due to six light scalar doublets vanish. GUT-threshold effect evaluated including all relevant superheavy scalar components in $(54_H, 1), (45_H, 1), (\overline{126}_H, 1)$, and $(10_H, 3_1 + 2 + 1)$ under $SO(10) \times G_f$ in the non-degenerate case is,

$$\frac{M_U}{M_U^0} = 10^{\pm 0.2004|\eta|}. \quad (15)$$

Even if the superheavy components are $10(\frac{1}{10})$ times heavier (lighter) than the GUT scale, the threshold effect gives,

$$\tau_p = 10^{34.0^{+1.54}_{-2.14}} \text{ yrs.} \quad (16)$$

where we have used eq.(13)-eq.(14). Clearly, this prediction is accessible to ongoing and planned searches for the decay mode $p \rightarrow e^+\pi^0$. Whereas in Model I the Majorana fermion Yukawa coupling f has to be fine tuned by 2 – 3 orders to get the desired heavy RH neutrino mass for the type-I see-saw scale, here we require $f \sim 0.1$. The light color-octet Higgs scalar with mass $M_C(1, 0, 8) \simeq 500$ GeV - few TeV is also accessible for detection at LHC , ILC or other accelerator searches with expectations for remarkable signatures [68, 69].

We find that when a triplet fermionic DM is used along with the complex color-octet scalar as in Case (ii) , exact unification scale is obtained for $M_U \simeq 10^{15}$ GeV. The deficit in proton lifetime prediction by a factor $10^{-2.7}$ below the experimental limit can be easily compensated by GUT-scale threshold effects and somewhat larger splitting with superheavy masses with $\sim 20(1/20)$ times heavier(lighter) than the GUT scale. However, when both the color-octet fermion $F_C(1, 0, 8)$ and the triplet DM are utilized having TeV scale masses as in Case (iii), the unification scale rises to ($\simeq 10^{16.9}$ GeV) and the GUT-scenario accommodates the triplet DM with a much more stable proton. Thus, like the single-step breaking case of Model I, with Pati-Salam intermediate symmetry too, unification is realizable with low-mass fermions alone apart from other possibilities. The derivation of light fermion masses from renormalizable Yukawa interaction are carried out in a manner similar to Model I with suitable GUT representations.

5.2 Other intermediate symmetries

In this section we briefly state our results obtained using other intermediate symmetries like $G_{224} \times S_4(g_{2L} \neq g_{2R})$ and $SU(2)_L \times SU(2)_R \times U(1)_{B-L} \times SU(3)_C \times S_4(g_{2L} = g_{2R})(\equiv G_{2213D})$.

With $G_{224} \times S_4$ intermediate symmetry and a light color-octet scalar of mass $M_C = 500$ GeV, we have observed excellent one-loop unification of couplings at $M_U^0 = 10^{15.7}$ GeV predicting $\tau_p \simeq 1.4 \times 10^{34}$ yrs. subject to threshold uncertainties. But the intermediate scale turns out to be smaller by a factor $(300)^{-1}$ than the desired value of the see-saw scale [10]. There has been a recent suggestion to accommodate neutrino masses and mixings with such lower seesaw scale [74]

With $G_{2213D} \times S_4$ intermediate symmetry, without using any additional low mass particles beyond the minimal requirement of six doublets of the HLM type model, although we achieve excellent unification with right value of M_R , the unification scale is found to be nearly 2 orders smaller than the lower bound imposed by the proton decay constraint. The other alternative for this model may be that, instead of being embedded in $SO(10) \times S_4$, it could emerge from a high scale trinification model like $SU(3)^3 \times S_4$. Other interesting possibilities through flavor-symmetric $SO(10) \times G_f$ will be investigated elsewhere.

6 Summary and Conclusion

In the absence of experimental evidences of supersymmetry, in this work we have attempted to implement manifest unification of gauge couplings in the HLM type model with $G_{213} \times S_4$ symmetry restoration at $\sim (1 - 10)$ TeV through the unifying symmetry $SO(10) \times G_f$ where $G_f = S_4, SO(3)_f, SU(3)_f$. Under the experimental lower bound on proton lifetime and the type-I seesaw scale constraint, we have carried out completion of grand unification successfully in two classes of models: Model I with single-step breaking and Model II with Pati-Salam intermediate symmetry.

A special distinguishing feature of the non-SUSY $G_{213} \times S_4$ model with six doublets at low scales is that it predicts the the color-octet fermion and the triplet fermionic DM as the non-trivial degrees of freedom missing from MSSM equivalents sans squarks and sleptons. As a result when these fields are switched on at the TeV scale, the model automatically predicts grand unification of gauge couplings with a non-SUSY GUT scale identical to the MSSM GUT scale ($\sim 10^{16}$ GeV).

Compared to the conventional $SO(10)$ prediction where the required color-octet fermion has been found to possess a very large mass, 7×10^{10} GeV, which can not be accessed by accelerator searches, in the present model of flavor-symmetric $SO(10) \times G_f$, the GUT-signals of both types of exotic fermions are subject to experimental tests at accelerator energies. Both these fermions belonging to the adjoint representation are shown to be light due to suitable values of the renormalizable Yukawa Lagrangian parameters. Phenomenology of light fermions is briefly outlined. Proton lifetime predictions are found to be accessible to ongoing or planned searches for $p \rightarrow e^+ \pi^0$. In two-step breaking model with Pati-Salam intermediate symmetry, several possibilities are pointed out also with experimentally accessible proton-lifetime predictions. Current phenomenological investigations suggest the triplet DM mass in the range 2.75 TeV - 4.5 TeV with the predicted positron excess and absence of anti-proton excess in agreement with indirect DM search experiments especially when the mass is on the higher side. The color-octet fermion pair production cross section and event rate are about one order larger than the heavy quark pair production case. These characteristics and absence of superpartners at LHC energies would point towards the existence of color-octet fermions. With color-octet fermion and the fermionic weak triplet DM masses being permitted near $\sim 1 - 5$ TeV, more interesting collider signatures are expected in the context of flavored grand unification which will be investigated separately.

In conclusion, we find that flavor symmetric standard gauge theory can be successfully embedded in $SO(10) \times G_f$ theory of fermion masses and unification of three forces with experimentally testable grand unification signals for observable proton decay and interesting collider signatures like weak-triplet DM as well as the color-octet fermion.

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